AIR SAMPLING EQUATIONS

Air Sampling Equations

Which equations are used in air sampling depend in part on the manner in which the air sample is analyzed.

There are two types of sample analysis:

1. Nuclide Specific (isotopic)

2. Gross Beta or Alpha

Two Types of Air Sample Analysis

1. Nuclide Specific Measurement

Individual nuclides (e.g. Cs-137) are quantified on the collection media, either by gamma spectroscopy using a germanium detector, or by radiochemistry.

2. Gross Beta and/or Alpha Measurement

Usually performed on an air filter using a gas-flow proportional counter, beta/alpha scintillator, GM or diode detector. In some cases, the collected material might be on an impactor plate instead of an air filter.

Nuclide Specific (Isotopic) Analyses of Air Samples

Collected Activity at End of Sampling

When an individual nuclide (e.g. Cs-137) in an air sample is quantified, it is possible to correct for the decay during sampling.

$$A_0 = \frac{CFE_c}{\lambda}(1 - e^{-\lambda t_s})$$

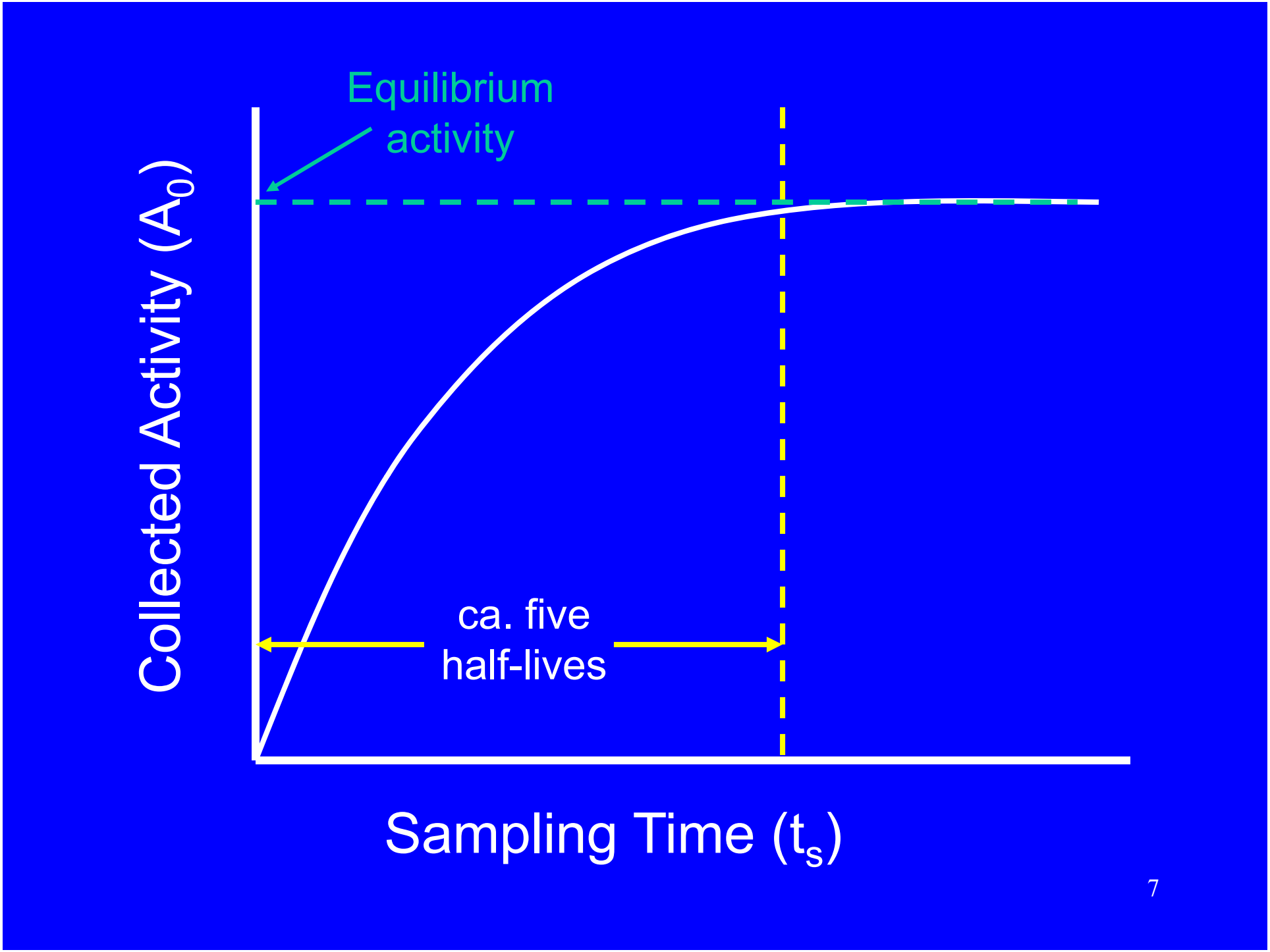
A_0 activity of the nuclide at the end of sampling (e.g., uCi)
C concentration of radionuclide in air (e.g., uCi/ml)
F sampling flow rate (e.g., ml/min)
E_c efficiency of collection
λ decay constant of radionuclide (e.g., min^{-1})
t_s sampling time (e.g., min)

Collected Activity at the End of Sampling when the Sampling Time (t_s) is longer than 5 half-lives of the Radionuclide

$$A_0 = \frac{CFE_c}{\lambda}$$

This is the maximum activity of a nuclide that can be collected. It is known as the saturation or equilibrium activity. At equilibrium, the activity being collected per unit time is equal to the amount of activity decaying per unit time.

Some people say that equilibrium/saturation is achieved when sampling has continued for seven or ten half lives rather than five half lives.


Equilibrium
activity
Collected Activity (A_0)
ca. five
half-lives
Sampling Time (t_s)

Collected Activity at the End of Sampling when the Sampling Time (t_s) is longer than 5 half-lives of the Radionuclide

$$A_0 = \frac{CFE_c}{\lambda}$$

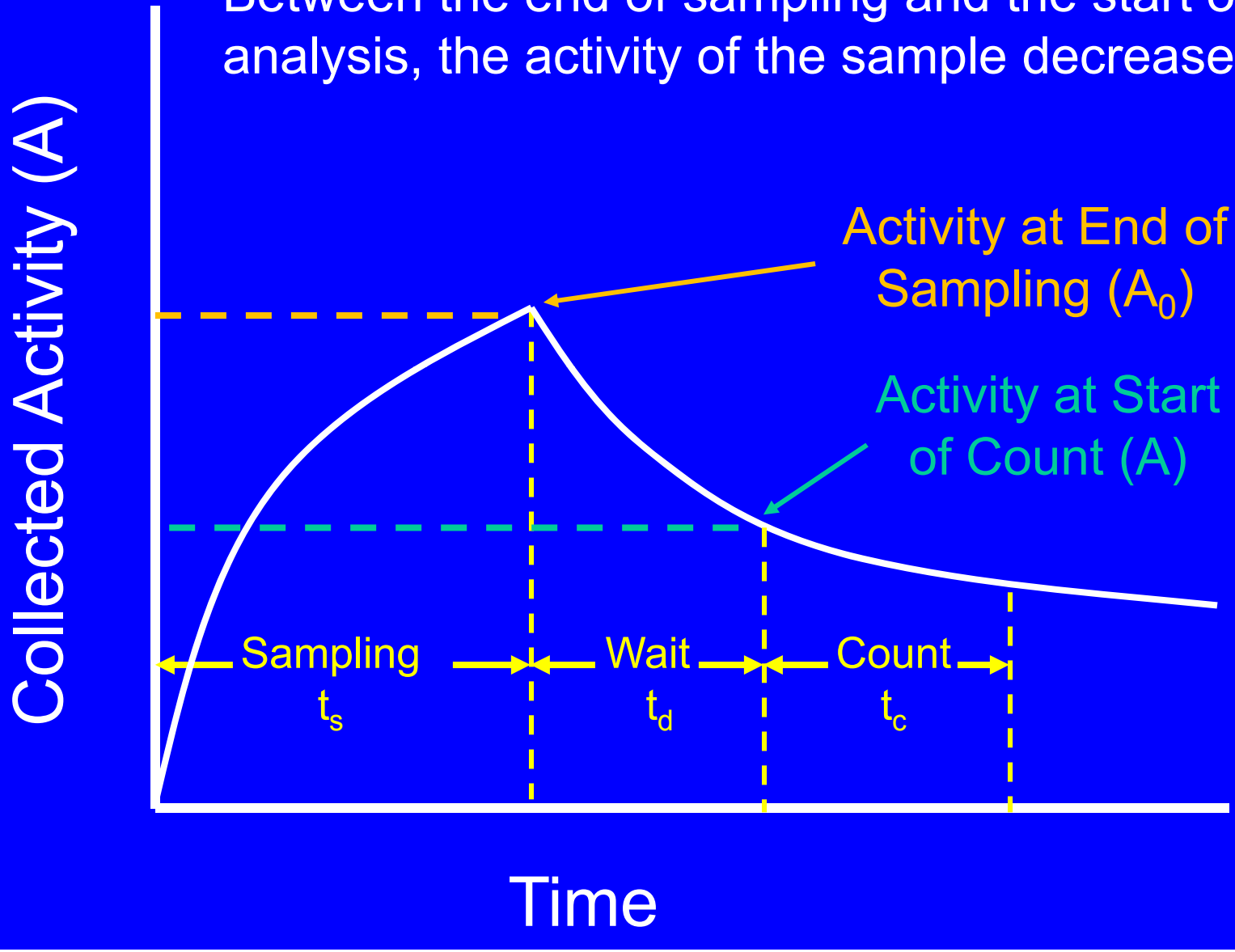
If the half-life of a nuclide is one hour, sampling longer than four hours won't increase the activity of the collected material by very much.

What can be done to increase the collected activity?

Sample using a higher flow rate.

Collected Activity at Start of Count

Between the end of sampling and the start of the analysis, the activity of the sample decreases.



Collected Activity at Start of Count

$$A = \frac{CFE_c}{\lambda}(1 - e^{-\lambda t_s})e^{-\lambda t_d}$$

A — activity of the nuclide at the start of the analysis (e.g., uCi)

t_d — time between the end of sampling and the start of the count (e.g., min)

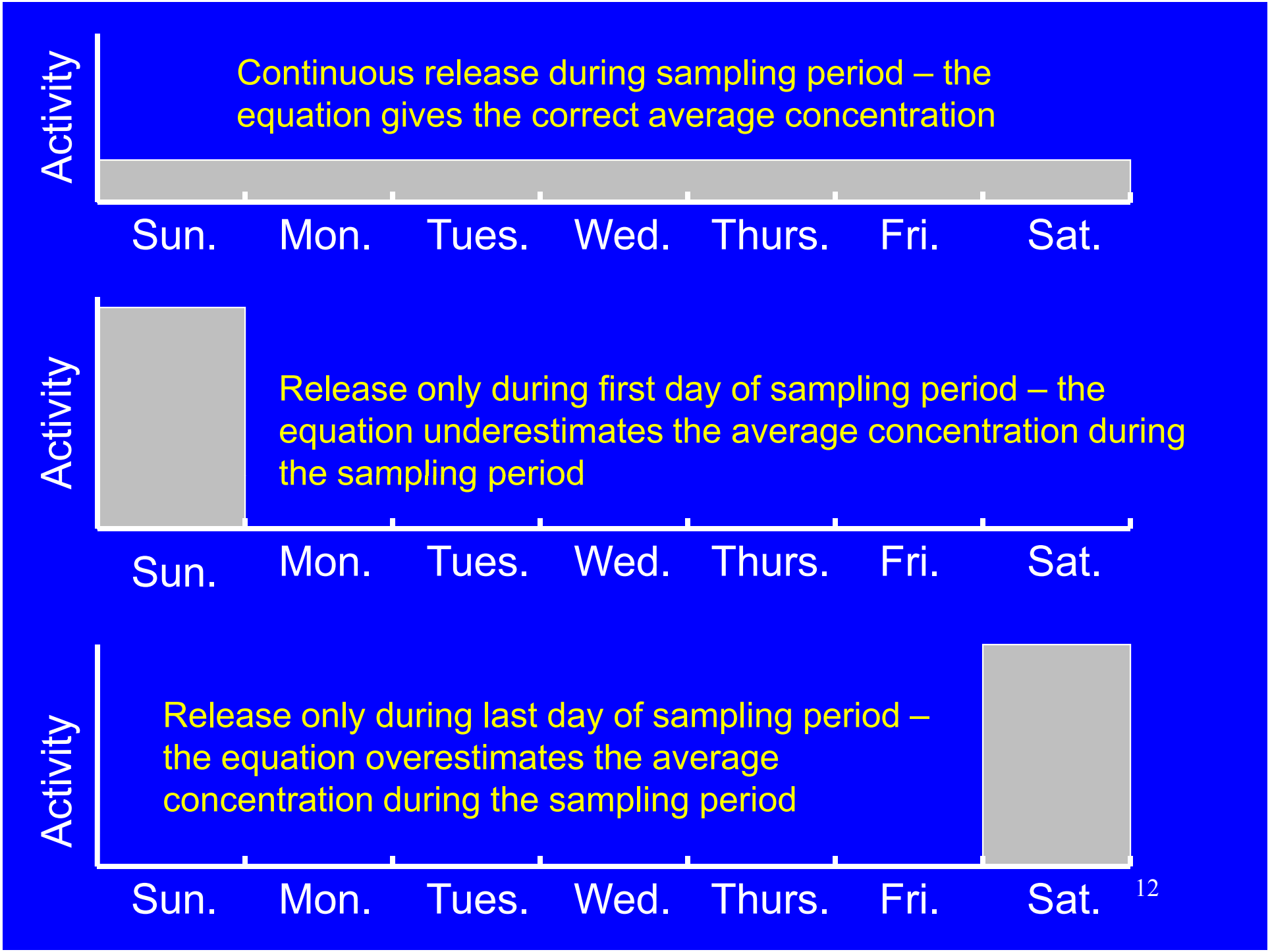
Airborne Concentration

$$C = \frac{A\lambda}{FE_c(1 - e^{-\lambda t_s})e^{-\lambda t_d}}$$

This is the key equation because it calculates the thing of interest: the concentration of the radionuclide in the air.

This equation assumes one thing: that the concentration in the air does not change during the sampling period.

If the concentration changes during the sampling period and the radionuclide half-life is short compared to the sampling period, the equation doesn't work.


Activity
Continuous release during sampling period – the equation gives the correct average concentration
Sun.
Mon.
Tues.
Wed.
Thurs.
Fri.
Sat.
Activity
Release only during first day of sampling period – the equation underestimates the average concentration during the sampling period
Sun.
Mon.
Tues.
Wed.
Thurs.
Fri.
Sat.
Activity
Release only during last day of sampling period – the equation overestimates the average concentration during the sampling period
Sun.
Mon.
Tues.
Wed.
Thurs.
Fri.
Sat.

Half-life is Much Longer Than Sampling Time

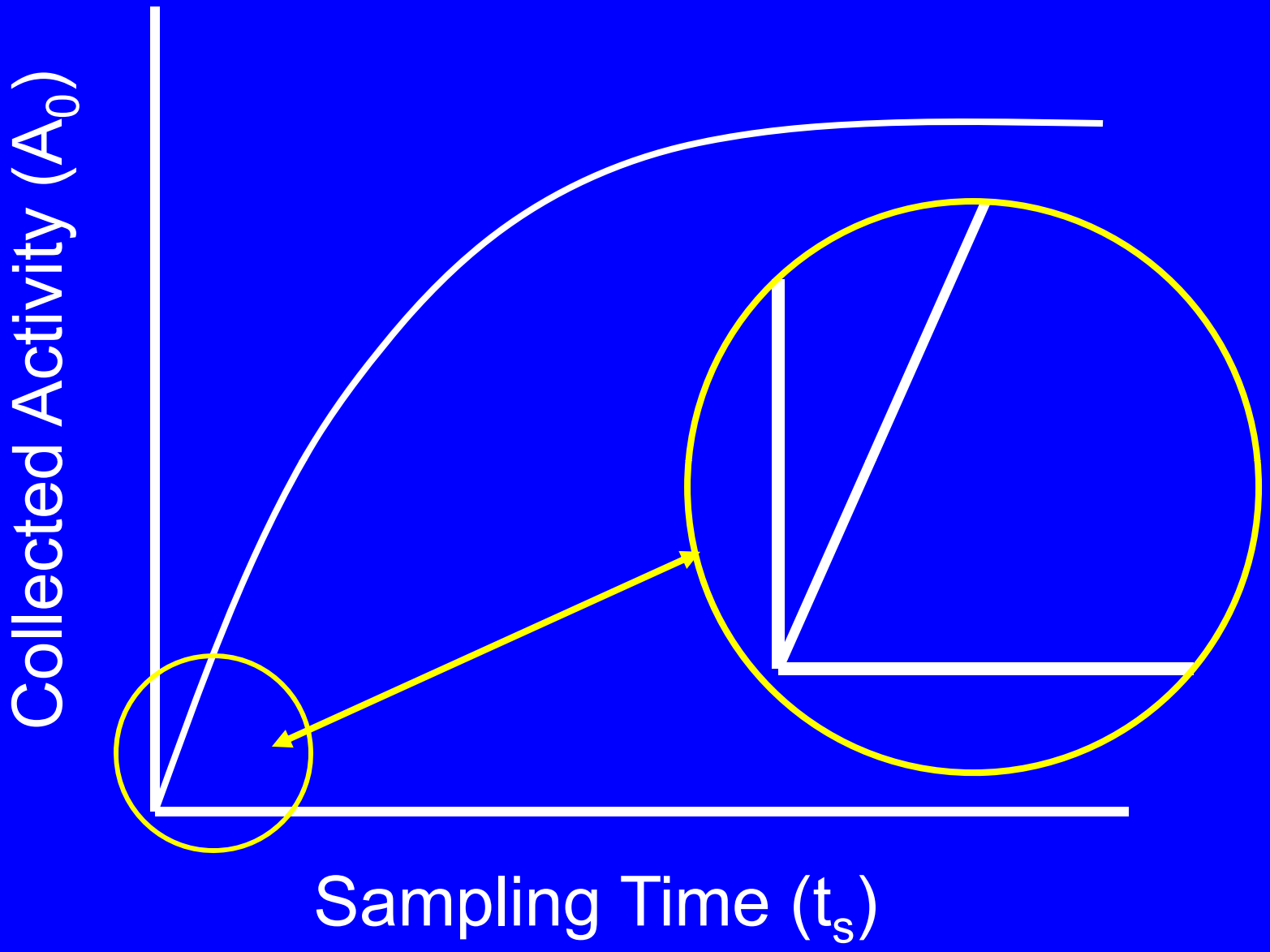
When the half-life of the radionuclide being collected is much longer than the sampling time, the previous complicated equation simplifies.

In this situation we haven't sampled nearly long enough to reach the saturation (equilibrium) activity.

As such, the collected activity increases linearly with sampling time. In addition, the activity of the collected sample will not decrease after sampling (or during the time the sample is being counted.

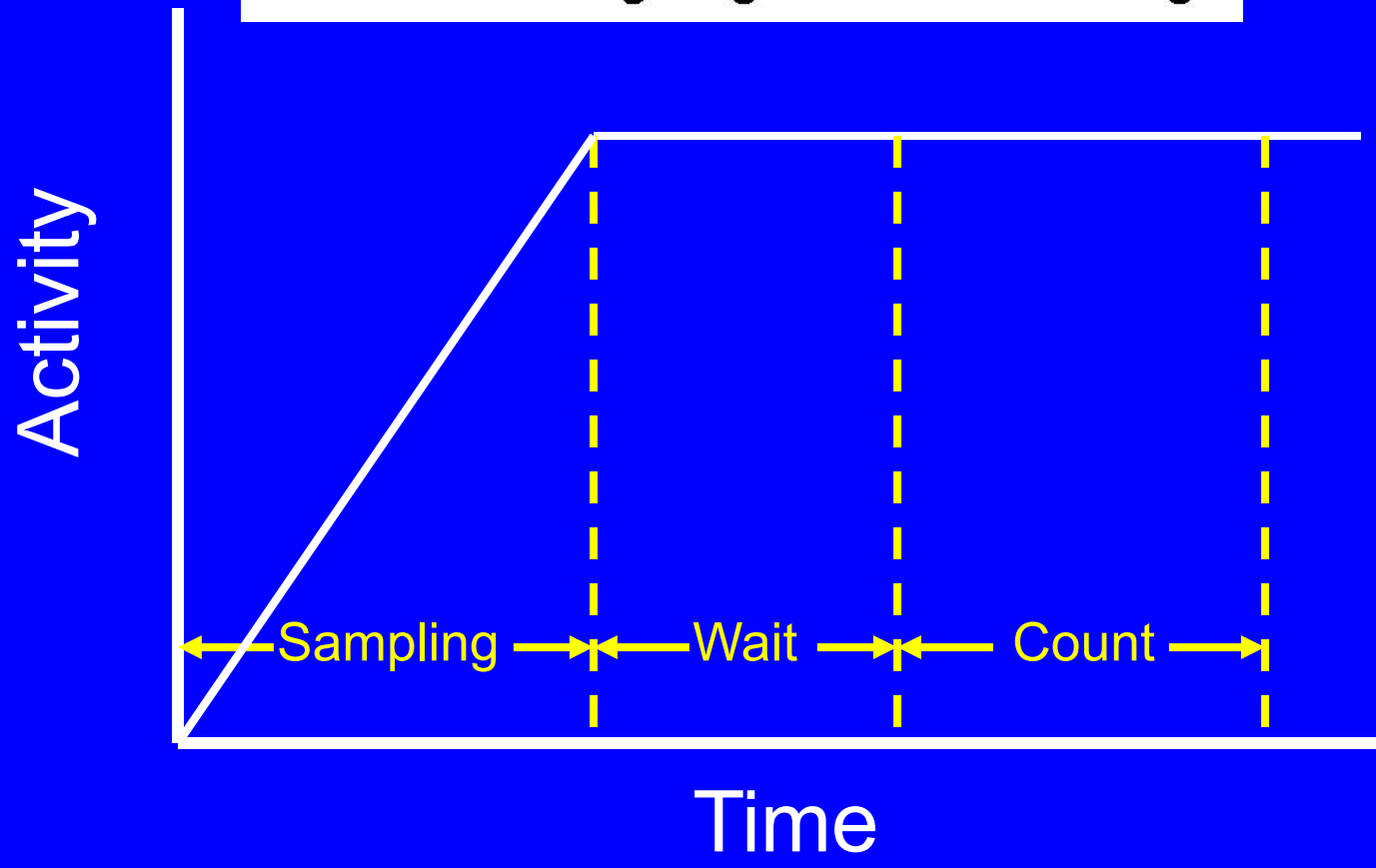
In practice, this is usually the case and the following simplified equations are more commonly employed than the complicated equation.

Half-life is Much Longer Than Sampling Time



Half-life is Much Longer Than Sampling Time

$$C = \frac{A}{F\, t_s\, E_c} = \frac{A}{V\, E_c}$$



Half-life is Much Longer Than Sampling Time

$$C = \frac{A}{F\, t_s\, E_c} = \frac{A}{V\, E_c}$$

When we calculate a concentration (e.g., uCi/ml) by dividing the sample activity with the volume (V) of air sampled, we are assuming that the radionuclide half-life was relatively long that there was no significant decay of activity during sampling.

The use of the above equation instead of the longer general equation can lead to mistakes if the radionuclide is short-lived.

Half-life is Much Longer Than Sampling Time

$$C = \frac{A}{F\, t_s\, E_c} = \frac{A}{V\, E_c}$$

If we use this simplified equation with a radionuclide that decays significantly during sampling, we will underestimate the concentration of the nuclide.

For example, we would underestimate the concentration of I-131 (8 d) by 4% if the sampling period were one day and by 25% if the sampling period were one week.

Sampling Time (t_S)	Underestimate of Concentration
the same as the radionuclide's half-life	28%
½ the radionuclide's half-life	15%
1/10 the radionuclide's half-life	3%
1/20 the radionuclide's half-life	1.7%

Determining the Collection Efficiency

The collection efficiency of filters for particulates is usually specified by the manufacturer.

This efficiency is specified for 0.3 um particles. This is a “worst case” scenario because the collection efficiency will be greater for particles smaller than 0.3 um and particles larger than 0.3 um.

In general, the higher the velocity of the air across the filter, the higher the collection efficiency. For some filters (e.g., many membrane filters), this effect is small. For other filters (e.g., cellulose filters) velocity can have a significant impact on collection efficiency.

In many “real-world” situations, the collection efficiency will be close to 1.0 (i.e., 100%).

Determining the Collection Efficiency

The collection efficiency of adsorber cartridges (e.g, charcoal) are usually specified by the manufacturer in the form of a curve (see next slide) that shows efficiency as a function of flow rate.

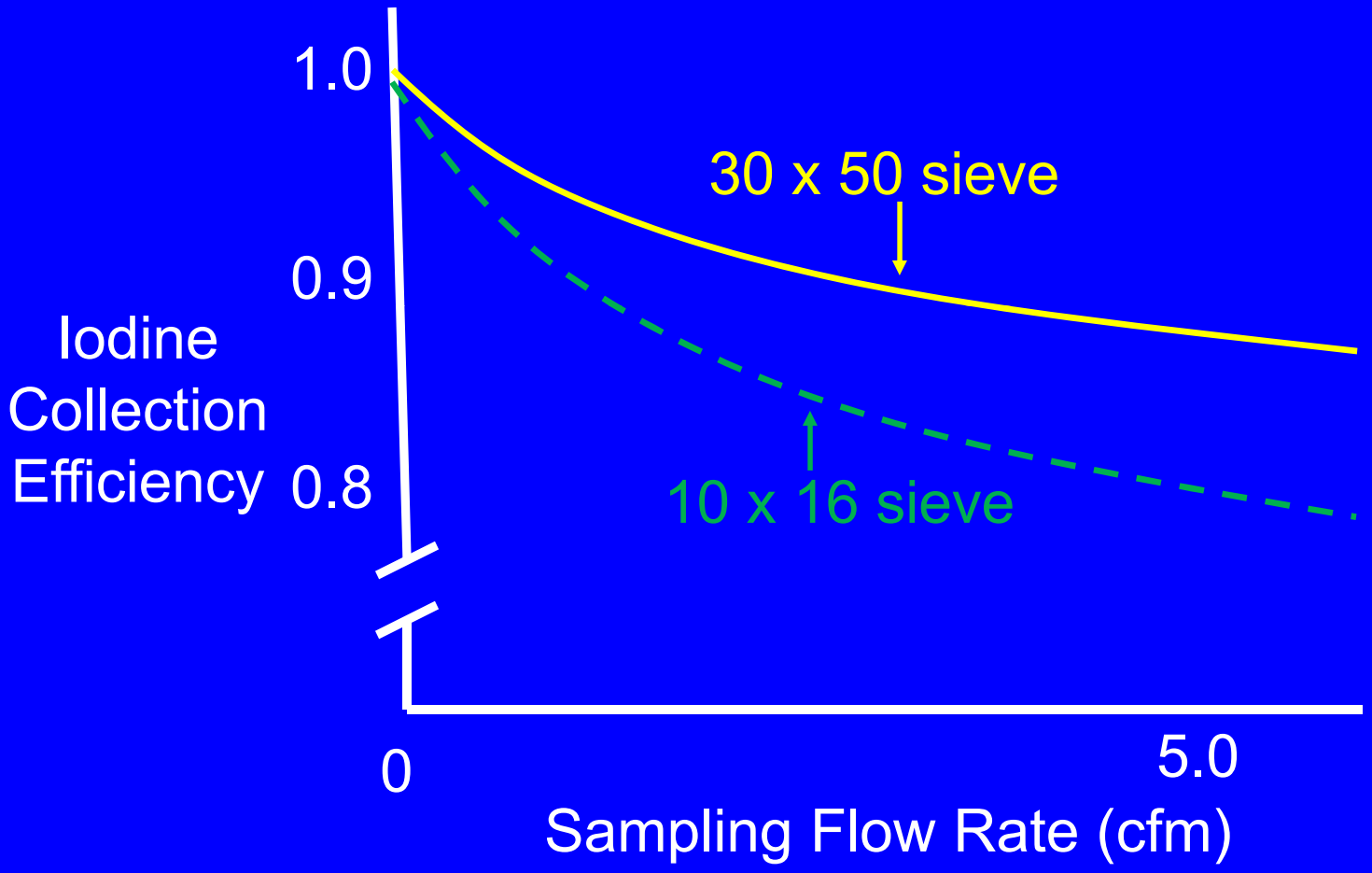
In the case of charcoal, the collection efficiency is specified for methyl iodide. This is a “worst case” scenario because the collection efficiency will be greater for elemental iodine.

The higher the flow rate through the adsorber, the lower the collection efficiency.

When adsorber cartridges are produced “in-house” the collection efficiency will have to be determined.

Determining the Collection Efficiency

Charcoal Collection Efficiency vs Sampling Flow Rate



Determining the Collection Efficiency

The collection efficiency of adsorber cartridges and absorber solutions can be determined by analyzing the activities collected in several identical collection devices operated in series. In the simplest case, two collection devices would be employed.

This method assumes that the collection efficiency is the same for the different devices, something that might not be true if there are different chemical or physical forms of the contaminant being sampled.

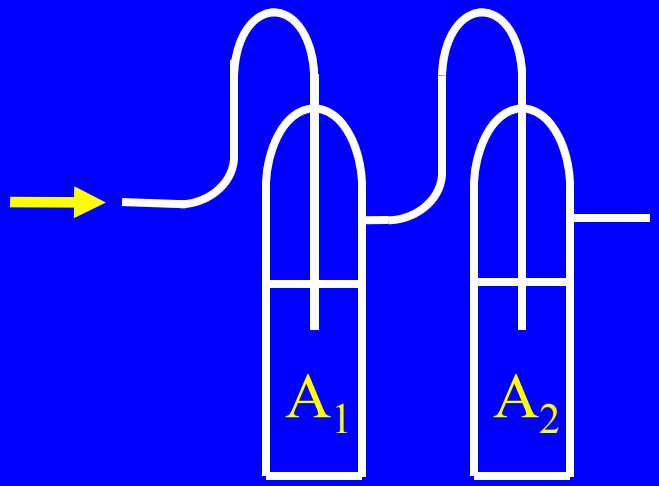
Determining the Collection Efficiency

$$E = 1 - \frac{A_2}{A_1}$$

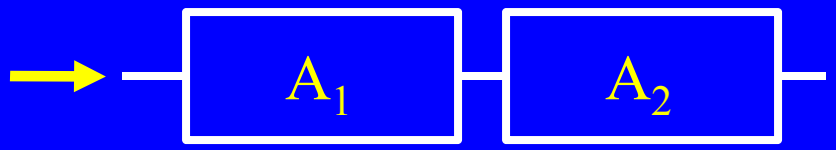
E is the collection efficiency

A_1 is the measured activity in the first collection device

A_2 is the measured activity in the second collection device



Bubblers



Adsorber Cartridges

Gross Beta or Alpha Analyses of Air Samples

Two Problems with Gross Alpha and Beta Measurements

1. In most cases, we cannot account for any decay of the sample activity because we don't know the half-life of the nuclide or nuclides in the sample. An exception might be a situation where the alpha or beta activity can only be due to a specific nuclide (in addition to the radon and thoron decay products).

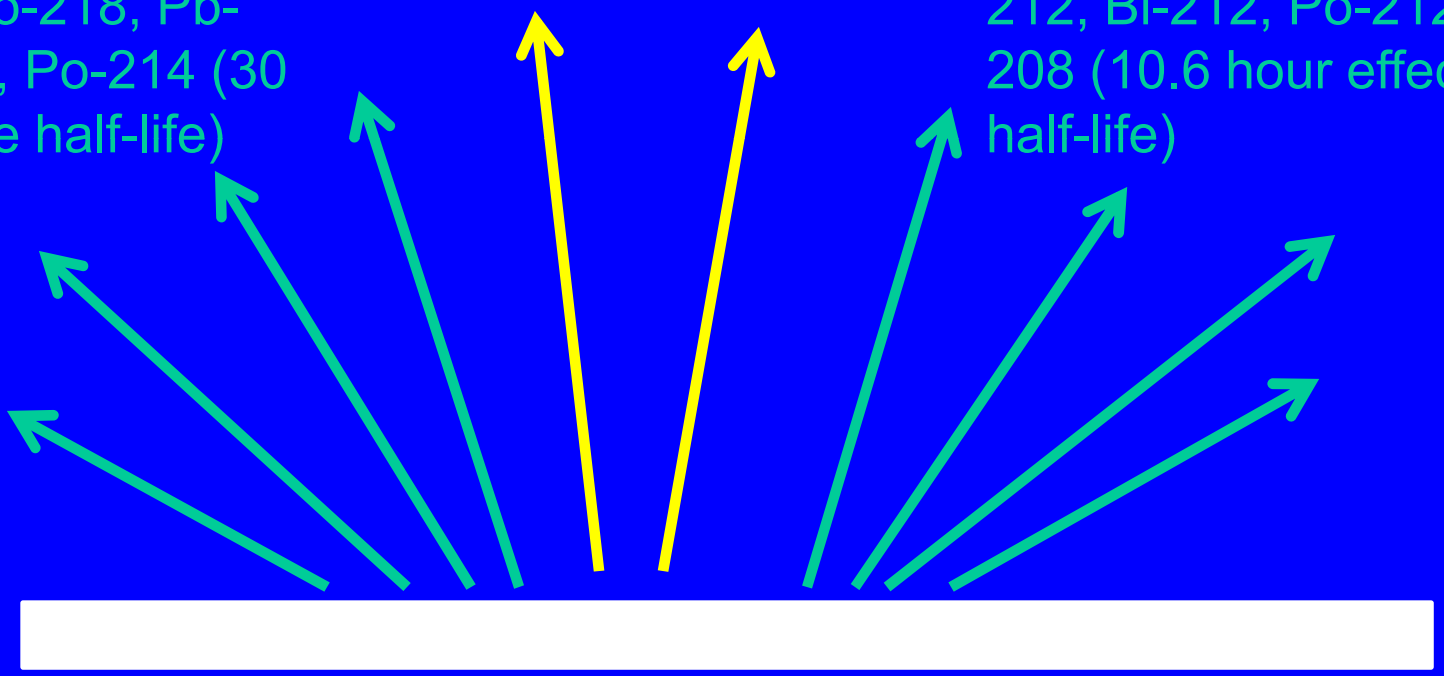
2. We only want to report the gross alpha/beta concentrations in the air of the licensed material, but many of the gross alpha and beta counts are due to naturally occurring radon and thoron decay products.

Problems with Gross Alpha and Beta Measurements

Alphas or betas from radon (Rn-222) decay products: Po-218, Pb-214, Bi-214, Po-214 (30 min effective half-life)

Alphas or betas from licensed material

Alphas or betas from thoron (Rn-220) decay products: Po-216, Pb-212, Bi-212, Po-212, Tl-208 (10.6 hour effective half-life)



Problems with Gross Alpha and Beta Measurements

Radon-222 Decay Products

Po-218 (3 min)
Alpha
↓
Pb-214 (27 min)
Beta
↓
Bi-214 (20 min)
Beta
↓
Po-214 (164 us)
Alpha

Radon-220 Decay Products

Po-216 (0.1 s)
Alpha
↓
Pb-212 (10.6 hr)
Beta
↓
Bi-212 (60 min)
Beta ↙ Alpha ↘
Po-212 (0.3 us) Alpha
Tl-208 (3 min) Beta

Problems with Gross Alpha and Beta Measurements

There are several ways to account for the contributions of radon and thoron decay products to the gross alpha and beta counts:

1. Wait a long time
2. The two-count method
3. Annular impactor
4. First count factor method

None of these methods are completely satisfactory.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

1. Wait a long time.

If we wait seven days after sampling to perform the gross alpha or beta count on the filter, the radon and thoron decay products will have decayed away.

The count then reflects the activity of the “licensed material.”

What we refer to as “licensed material” also includes the contributions from long-lived natural material (NORM).

Clearly, waiting seven days after sampling would not be acceptable if the licensed material were short-lived.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

2. Two Count Method

This method involves counting the filter twice.

The first count (C_1) is approximately 4 hours after sampling.

The second count (C_2) is approximately10 – 20 hours after sampling.

The time between the first and second count (Δt) is one to two half-lives of the thoron decay products.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

2. Two Count Method

The first count is due to the “licensed material” plus thoron decay products. Since the first count was four or so hours after sampling, the radon (Rn-222) decay products (30 min half-life) would have decayed away.

The second count is also due to the “licensed material” and long lived naturally occurring airborne radionuclides plus thoron (Rn-220) decay products. However, the thoron decay products have decreased in activity.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

2. Two Count Method

The corrected first count (C_{C1}) represents the first count due to the "licensed material" without any contribution from thoron or radon decay products.

$$C_{C1} = \frac{C_2 - C_1 e^{-0.0654\,\Delta t}}{e^{-\lambda \Delta t} - e^{-0.0654\,\Delta t}}$$

λ is the decay constant of the "licensed material" (hr^{-1})

0.0654 is the decay constant for thoron decay products (hr^{-1})

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

2. Two Count Method

In many situations, the "licensed material" is long-lived and the equation simplifies somewhat to:

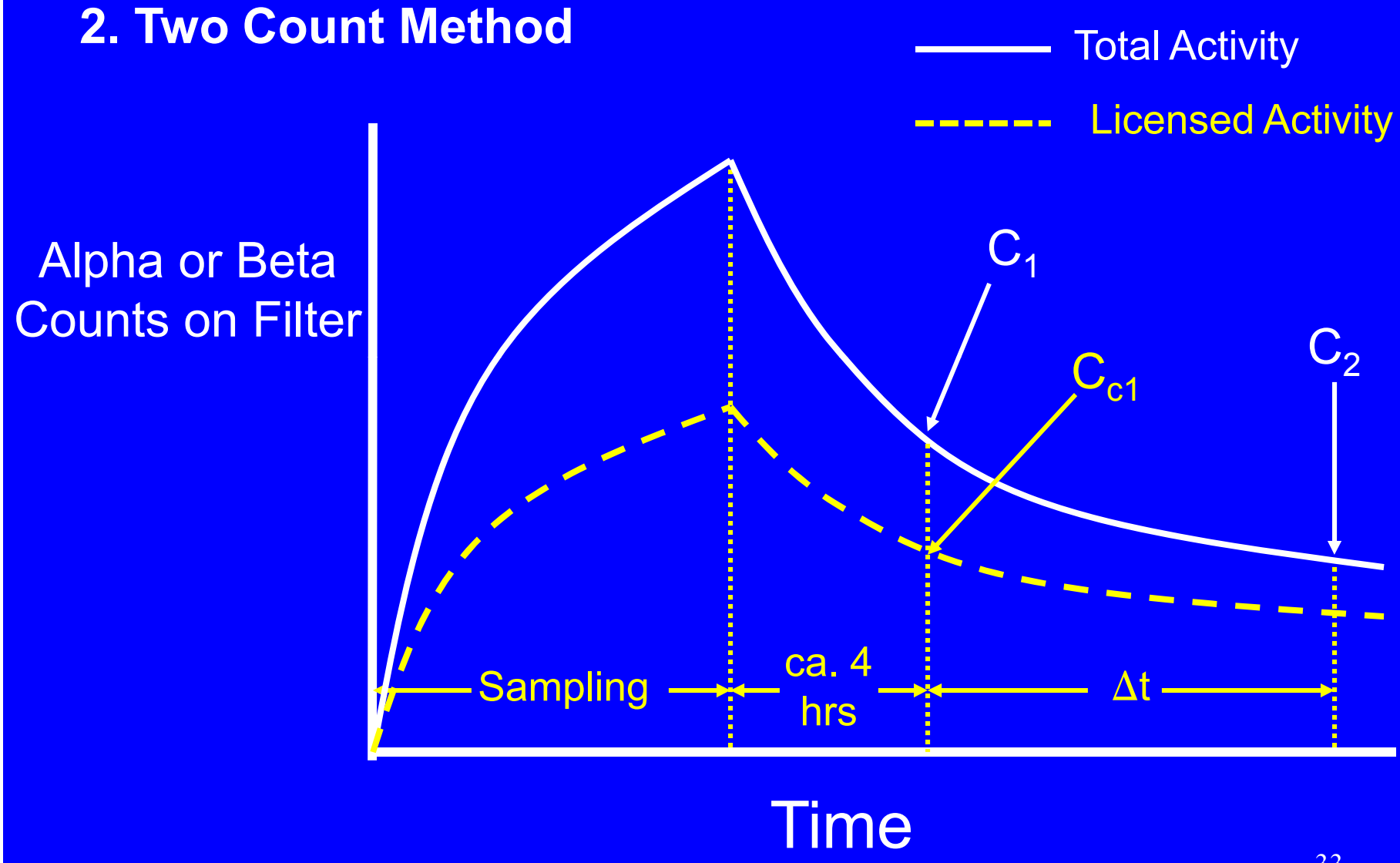
$$C_{Cl} = \frac{C_2 - C_1 e^{-0.0654\,\Delta t}}{1 - e^{-0.0654\,\Delta t}}$$

The next figure summarizes what is going on.

We are only interested in the "licensed material", but our actual measurements (counts) are of the total activity.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

2. Two Count Method



Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

3. Annular Impactor

The annular impactor only collects particles with diameters ≥ 1 um.

The assumption is that the naturally occurring radon and thoron decay products are attached to airborne particulates that are smaller than 1 um while “licensed material” is typically associated with airborne particulates larger than 1 um.

These assumptions are usually correct, although any fumes of licensed material would be smaller than 1 um.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

3. Annular Impactor

With a typical design, air enters the relatively large holes in the bottom of the annular impactor. As the airstream moves upwards, it increases in velocity because the channel through which the air is travelling decreases in cross section.

At the top of the unit the airstream makes a 180 turn. The significant momentum of the larger particulates (i.e., licensed material) prevents them from making the 180 turn. As a result, they impact onto the collection plate/planchet.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

3. Annular Impactor

There might be a fine film of oil applied to the collection plate/planchet in order to retain the impacted particles.

Alternatively, a glass fiber filter might be glued to the planchet - this will act as a substrate that will hold onto the impacted particles.

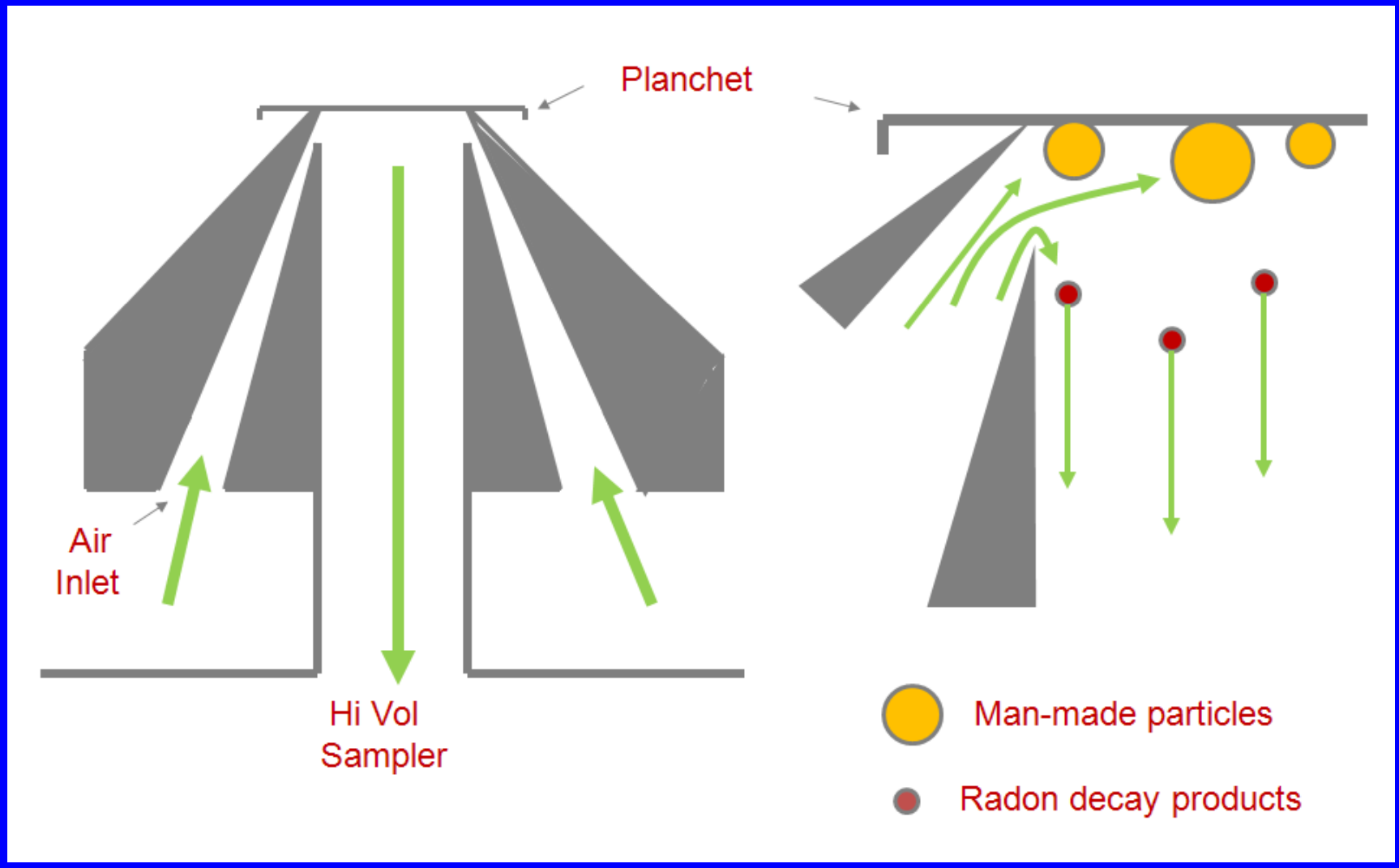
The small particulates (i.e., radon and thoron decay products) have less momentum. As such, they make the 180 degree turn and are not collected.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

3. Annular Impactor

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

3. Annular Impactor



Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

4. First Count Factor

This is a “quick and dirty” method to determine if there has been a release resulting in airborne alpha or beta activity.

It can also estimate the alpha or beta contribution from the released material.

It involves sampling particulates for a standardized time at a specific flow rate, waiting for a specific period and counting for a specific period. The times and flow rate must always be the same.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

4. First Count Factor

The filter is analyzed for beta and alpha activity.

The “First Count Factor” is the beta to alpha ratio”

$$\Gamma = \frac{B}{A}$$

Before the method can be used, the beta to alpha ratio due to radon decay products must be determined in the absence of licensed material.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

4. First Count Factor

Before the method can be used, the beta to alpha ratio due to radon decay products must be determined in the absence of licensed material.

The typical back ground beta to alpha ratio due to radon decay products might be in the 1.8 to 2.5 range.

If the filter is counted immediately after sampling so that the Po-218 hasn't had time to decay very much, the ratio might be closer to 1.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

4. First Count Factor

As an example, lets imagine that the beta to alpha ratio due to radon decay products was observed to range from 1.8 to 2.5 and that the average ratio ($\bar{\Gamma}$) was 2.

Then, if a beta to alpha ratio above 2.5 is seen in the workplace, it suggests that there has been a release of a beta emitter.

If a ratio is subsequently observed below 1.8, it would suggest that an alpha emitter was released.

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

4. First Count Factor

The observed ratio might be outside the range of ratios normally associated with radon decay products, but it still might be due to radon decay products with no contribution from licensed material.

To evaluate this possibility, the beta and alpha counts might be repeated 30 minutes later. If the counts drop in half, we can conclude that they were only due to radon decay products.

If the counts do not drop in half, they were due to “licensed material.”

Correcting for Radon and Thoron Decay Product Contribution to Gross Alpha or Beta Counts

4. First Count Factor

If there was an alpha release, the alpha activity due to the released alpha emitter can be calculated with this equation:

$$A_M = B\left(\frac{1}{\Gamma} - \frac{1}{\overline{\Gamma}}\right)$$

If there was a beta release, the alpha activity due to the released beta emitter can be calculated with this equation:

$$B_M = A\left(\Gamma - \overline{\Gamma}\right)$$

Appendix

Measuring the Activity at the Start of the Count

Count Rate at Start of Count

With short-lived nuclides, the count rate is higher at the start of the count than at the end. The following equation corrects for any decrease in count rate during the count time. It calculates the count rate at the start of the count.

$$R = \frac{N\lambda}{(1 - e^{-\lambda t_c})}$$

N	net counts during the count time
t_c	count time (e.g., min)

Measured Activity at Start of Count

The activity of short-lived nuclides is higher at the start of the count than at the end. The following equation corrects for any decrease in sample activity of short-lived nuclides during the count time. It calculates the activity at the start of the count.

$$A = \frac{N\lambda}{E_D I(1 - e^{-\lambda t_c})}$$

N	net counts during the count time
E_D	detector efficiency (e.g., counts/gamma)
I	intensity/yield/abundance of radiation (e.g., gammas/decay)
t_c	count time (e.g., min)